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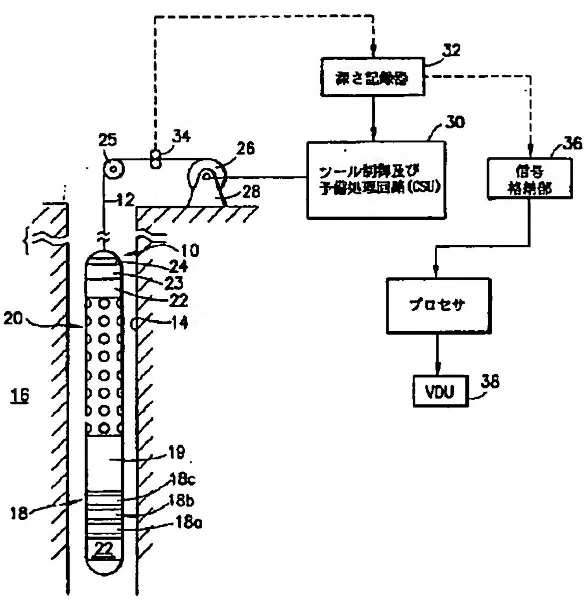
(54)【発明の名称】　ボアホール音波反射検層用方法及び装置

(57)【要約】

【課題】　広い範囲の地層にわたり測定することを可能とする反射音波検層技術を提供する。

【解決手段】　ボアホール（14）周りの地層の画像形成を行なう方法が提供され、それは、ボアホールの直径を決定し、地層の音波減衰特性を決定し、ボアホールから地層内への探査深さに対する興味のある範囲を決定し、ボアホール内にツール（10）を位置させ該ツールから地層内へ音波信号を送信し、地層内の構造物によって反射された音波信号を該ツールで受信し、受信した音波信号を解析してボアホールから反射構造物の距離を決定し、且つ決定した距離に基いてボアホールに関し反射構造物の位置の画像を発生する、上記各ステップを有している。該ツールは少なくとも1個の単極送信器（18）と探査深さの興味のある範囲にしたがって選択された距離だけ該送信器から離隔されている少なくとも1個の音波受信器（20）を有している。音波信号の周波数は、ボアホールの直径、地層の音波減衰特性、探査深さの興味のある範囲にしたがって選択される。



【０００１】
【発明の属する技術分野】本発明は、ボアホール内において発生され且つ受信された音波信号を使用してボアホールの周りの地層内の音波反射体を検知することを含むボアホール検層に使用する方法及び装置に関するものである。
【０００２】
【従来の技術】地層の特性づけのための音波技術は公知である。これらの技術の全ては、供給源から興味のある地層を介して受信器へ音波信号を送信することを行なう。該信号の周波数は、地震適用例における非常に低い周波数から、使用される特定の技術に依存して、音波周波数を介し超音波周波数へ変化することが可能である。殆どのボアホールロギング即ち穿孔検層では、ボアホールの壁における地層を介して供給源から実質的に直接的に受信器へ通過する音波信号に対する時間の測定を行なう。しばしば、この測定は、これらの直接的到達を記録し且つ反射に基く信号を排除すべく設計される。一方、受信信号をフィルタして反射に起因する信号を除去する場合がある。
【０００３】地震探査は、大略、地表面下側の構造を検知するために典型的に非常に低い周波数において反射音波信号を使用する。信号供給源及び／又は検知器は、通常、地表に位置されている。ボアホール地震技術はこれらのうちの１つをボアホールの内側に配置させる。
【０００４】ボアホール音波反射探査においては、同一のボアホール内に配置した音波送信器及び受信器で測定が行なわれる。この形態は、ボアホール軸に関し小さな角度を有する音波反射体からの反射波フィールドを記録するのに最もよく適している。例えば、ほぼ垂直な断口、断層及び岩塩ドーム側面はほぼ垂直なウエル即ちさく井に対する良好なボアホール反射ターゲットである。ほぼ水平な床境界、流体接触界面（気体／石油又は石油／水）及び貯留箇所内部の鉱条は高度に離れており且つ水平なウエル即ちさく井に対する良好なターゲットである。ボアホール反射探査における所望のイベント（反射）は、ボアホールから地層の反射体へ伝播し且つボアホールへ戻ってくる波動である。然しながら、送信器からの音波エネルギの著しい部分は直接的に受信器アレイへ伝播する。これらの直接的な波動は圧縮性及び剪断性ヘッドウエーブ（ヘッド波）、チューブウエーブ（ストンレー波）、流体及びボアホールモード及びさく井にケーシングが設けられている場合には種々のケーシングモードを包含している。直接的な波は、更に、ツール本体に沿って伝播する種々のツールモードを包含する場合がある。音波検層適用例においては、これらの直接的な波のうちの幾つか、例えばヘッド波及びストンレー波、を使用して地層の特性を検層する。然しながら、反射探査適用例においては、それらは不所望のものである。これらの直接波は、典型的に、反射波よりも著しく大きなものである。
【０００５】ダウンホール音波測定を使用してさく井周りの反射画像形成は、特に、ボアホールと相対的に貯留箇所の上部又は底部の位置を決定するために水平なさく井において使用するために従来提案されていた。米国特許第４，８３３，６５８号は、水平なさく井周りの反射体の位置を決定するために信号を処理する方法を開示している。図１は上記米国特許に記載されているシステムを示している。ツール（装置）５は、地表にあるドリル用デリック３１へ結合されているドリルストリング３０の端部において水平方向のボアホール１内に位置されている４個の送信器E_1－E_4及び１２個の受信器R_1－R_{12}を有している。これらの送信器は一定の間隔、例えば０．２５ｍに等しい間隔で互いに離隔されており且つ受信器は一定の間隔、例えば１ｍに等しい間隔で互いに離隔されている。最も近い送信器と受信器との離隔は１ｍとして提案されている。該ツールの長さは、高々、ボアホールと興味のある最も離れた反射構成体（界面１３，１５）との間の距離に等しく選択されている。ツール５はボアホール１に沿って検層され且つ送信器Ｅは５，０００乃至１０，０００Ｈｚの範囲内の周波数で音波信号を発生し、且つ受信器Ｒは直接波及び反射波の両方を受信する。受信信号を解析して、直接（回折）波及び反射波の平均伝播速度を決定する。反射波に対応する信号から時間セクションが決定され、この時間セクションは反射波の平均伝播速度によって深さセクションへ変換される。反射用界面の位置はこの深さセクションから決定される。上記’６５８特許において提案されているアプローチ及びパラメータはある場合には動作するが、動作しない場合が多数ある。該’６５８特許は、このことを認識しておらず且つ全ての状況において動作することを可能とする技術に対する適宜の修正について提案するものではない。
【０００６】
【発明が解決しようとする課題】本発明は、以上の点に鑑みなされたものであって、上述した問題がそれ程深刻なものではなく且つより幅広の地層範囲にわたって測定を行なうことを可能とする反射音波検層技術を提供することを目的とする。
【０００７】
【課題を解決するための手段】本発明に基くボアホール周りの地層の画像形成を行なう方法は、ボアホールの直径を決定し、地層の音波減衰特性を決定し、ボアホールから地層内への探査深さ用の興味のある範囲を決定し、少なくとも１個の単極送信器と探査深さの興味のある範囲にしたがって選択された距離だけ該送信器から離隔されている少なくとも１個の音波受信器を具備するツールをボアホール内に位置決めし、前記少なくとも１個の単極送信器でボアホールの直径と、地層の音波減衰特性と、探査深さの興味のある範囲とにしたがって選択され

とが可能である。これらの減衰器及びそれらの機能については本明細書に取込んだ同時係属出願の米国特許出願第０８／５２７，７３６号に詳細に記載されている。このような減衰器は、必要に応じ、送信器と減衰器アレイとの間において使用することも可能である。オリエンテーション装置（例えば、磁力計及び加速度計を含むシュルンベルジェ社のＧＰＩＴツール）２３及びテレメトリーカートリッジ２４が設けられることによって本ダウンホールツールが完成される。

【００１５】ツール１０はボアホール１４を上下に移動すべく適合されており、且つツール１０が移動すると、送信器１８は周期的に音波信号を発生する。発生された音波信号はボアホールを介し及び／又は地層を介して伝播し、そこで地下構造物によって反射され、且つ受信器アレイ２０における受信器が、典型的に、発生された信号から得られる何等かのエネルギを検知する。ボアホール内においてツール１０を移動させるメカニズムは、地層の地表における滑車ホイール２５へ延在し、次いで適宜のドラム及びウインチメカニズム２６へ延在するケーブル１２を有しており、ドラム及びウインチメカニズム２６は所望に応じツール１０をボアホール内において昇降動作させる。送信器アレイ１８及び受信器アレイ２０と地表の装置との間の電気的接続は、ドラム及びウインチメカニズム２６と関連している多要素スリップリング及びブラシコンタクト組立体２８を介して行なわれている。ユニット３０は、ツール１０へ電気的信号を送り且つそれからケーブル１２及び組立体２８を介してその他の電気的信号（音波ログ）を受け取るツール制御及び予備処理回路を有している。ユニット３０は、受信器アレイ２０からの信号をボアホール１４内のそれぞれの深さレベルと関連させるために、深さ測定ホイール３４から深さレベル信号を派生する深さ記録器３２と共働する。受信器アレイ２０の出力は、ユニット３０におけるオプションとしての予備処理の後に、信号格納部３６へ送られ、信号格納部３６は、更に、音波信号出力をボアホール１４内のそれぞれの深さレベルと関連づけるために深さ記録器３２から又はそれを介しての信号を受取ることが可能である。格納部３６はデジタル音波ログ測定値の形態で受信器アレイ２０の出力を格納することが可能である。格納部３６は、例えばディスク又はテープ等の磁気記録装置、及び／又は例えば半導体又は等価のメモリ回路等のその他の格納媒体を有することが可能である。次いで、格納されたデジタルデータを処理してボアホール周りの地下の地層の画像をプリント画像又はＶＤＵ３８上の表示として与えることが可能である。地震処理において一般的に使用されているようなデータのキルヒホフ型マイグレーションを使用してボアホール周りの反射構造物の画像を派生させる。

【００１６】各送信器１８ａ，１８ｂ，１８ｃは実質的に米国特許第５，０４３，９５２号（引用により本明細書に導入する）において記載されており且つ図３に示した単極源を有している。これらは従来の音波検層適用例において使用されている単極源と実質的に同じものである。該供給源は、波型容器４４によって画定される油を充填したキャビティ４２内に保持されているピエゾセラミック円筒４０を有しており、容器４４の波型が波型容器外側のマッド（泥水）と波型容器内側のオイルとの間の差動的体積変化を可能としている。該円筒を半径方向にポーリングするために電極４６を介してパワーアンプがピエゾセラミック円筒４０へ取付けられている。電極４６は該円筒へ電圧を印加するためにピエゾセラミック円筒４０の内側表面及び外側表面へ取付けられており、該電圧は該円筒の長さ及び半径を拡大させ、その際に体積膨脹によってボアホール内へ圧縮波が発生され且つ伝播され、且つ圧縮波及び剪断波の両方が地層内へ伝播される。

【００１７】充分に音波エネルギを放射させるために、送信器１８は不可避的に長い時間にわたりリンギングするほぼ幾何学的共振で動作すべく設計されている。このリンギングを停止させるためにダンピングメカニズムが導入されており、それは音波信号供給源に対してはゴムタングステン裏張り物質４８を有しており、それを取付けた構成に対して良好なインピーダンス整合とダンピングとを与えている。このゴムタングステン裏張りは、更に、トランスデューサが液体内に浸漬された場合に付加的な流体モード励起を防止している。このゴムタングステン複合体は、タングステン粉末で充填させたブチルゴム骨格体を有している。該裏張りのインピーダンス及び減衰は、タングステンの百分率、該粉末の圧縮度、加硫度及びゴムの粉末に対する接着度に依存している。

【００１８】図２において、３個の送信器が示されているが、本発明はこれよりも多数又は少数の送信器で実施することが可能であることは勿論である。例えば、２個の送信器は３０フィート（９．１４ｍ）の程度の探査深さ範囲を与えることが可能であり、それはある環境においては適切な場合がある。送信器の間の間隔は、広範囲の探査深さを達成すべく選択されている。送信器１８ａと１８ｂとの間の間隔は約４フィート（１．２２ｍ）であり、且つ送信器１８ｂと１８ｃとの間の間隔は約３フィート６インチ（１．０７ｍ）である。与えられた環境に対して最良の間隔を選択するための検討事項については以下により詳細に説明する。供給源出力をモニタする目的のために送信器１８ｃにおいてハイドロフォンが位置されている。このハイドロフォンは、オプションとして、短い間隔とした受信器として使用することも可能である。送信器１８ｃと受信器との間の間隔は、探査深さを増加させるために増加させることが可能である。一方、送信器の間の間隔は複数個の探査深さを与えるために増加させることが可能である。

【００１９】受信器アレイ２０は垂直方向に６インチ

一の技術を使用して画像が生成される。従って、画像はボアホール軸（深さ軸）にそって且つボアホール周りに方位角的に生成することが可能である。各方位角ハイドロフォン位置において完全な波形を記録することによって、与えられた反射波が各位置において検知される時間を決定し、従ってどの方向からそれが到達したかを決定することが可能となる。例えば、水平方向のボアホールにおいては、最初に最も上側のハイドロフォンによってある反射が検知され、次いでより下側のハイドロフォンにおいて検知される場合には、その反射構造物はボアホールの上側に存在するものとして識別することが可能であり、且つその反対の場合には、反射体はボアホールの下側にあるものとして識別することが可能である。

【００３３】ボアホールにおいて反射測定を行なう上述した装置は、既知の態様で地層特性の評価を行なうために従来の回折データを得るために使用することが可能な場合があり、その場合には、例えばヘッドウエーブ測定等の本発明にとって不必要と考えられる測定を使用して地層パラメータを決定することが可能な場合がある。更に、上述した一般的なアプローチは、ウエル即ちさく井が充分に近接している場合には、交差ウエル（さく井）画像形成に適用することも可能である。

【００３４】本発明は、ワイヤライン及びドリリングしながらの検層適用例の両方に適用可能である。ＬＷＤ適用においては、前に提案したＬＷＤ音波検層ツールの態様で、ドリルビット上方の底部孔組立体の一部を形成する。

【００３５】以上、本発明の具体的実施の態様について詳細に説明したが、本発明は、これら具体例にのみ限定されるべきものではなく、本発明の技術的範囲を逸脱することなしに種々の変形が可能であることは勿論である。

【図面の簡単な説明】

【図１】　従来のボアホール反射画像形成システムを示した概略図。

【図２】　本発明に基くボアホール反射画像形成システムを示した概略図。

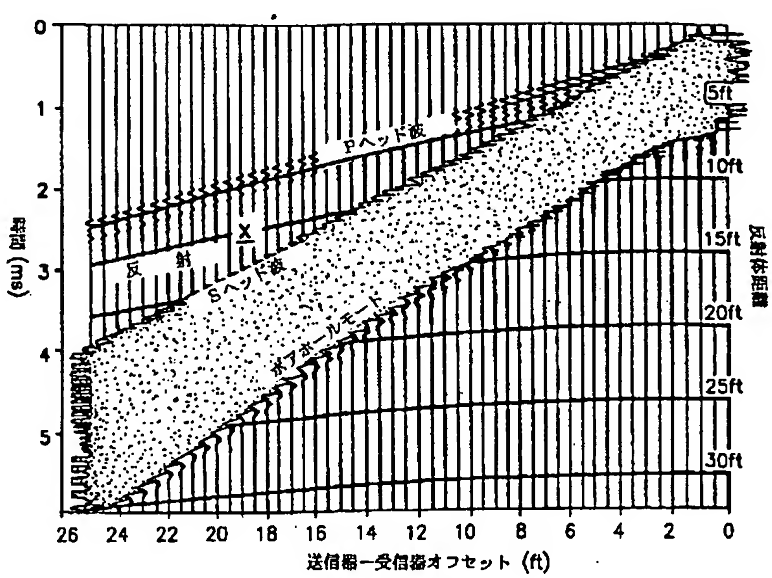
【図３】　本発明に使用可能な単極供給源を示した概略断面図。

【図４】　反射信号の検知を制限するヘッドウエーブ到達を示したグラフ図。

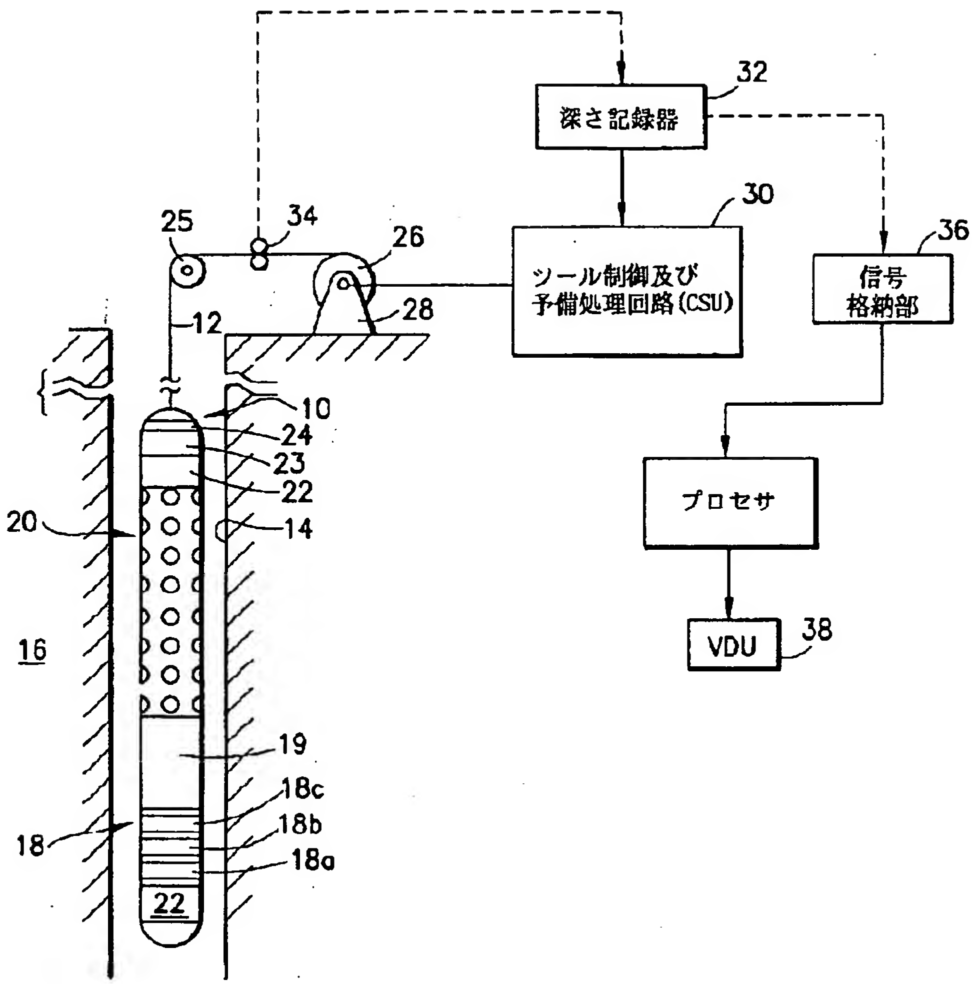
【符号の説明】

１０　音波反射画像形成ツール
１２　ケーブル
１４　ボアホール
１６　地層
１８　送信器
１９　離隔体
２０　受信器アレイ
２２　減衰器
２３　オリエンテーション装置
２４　テレメトリーカートリッジ
３０　ツール制御及び予備処理回路
３２　深さ記録器
３６　信号格納部
３８　ＶＤＵ（ビデオディスプレイユニット）

【図４】



【図2】



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METHOD AND APPARATUS FOR BOREHOLE ACOUSTIC REFLECTION LOGGING

FIELD OF THE INVENTION

The present application relates to a method and apparatus for use in borehole logging which involves detecting acoustic reflectors in the formation surrounding a borehole using acoustic signals generated and received in the borehole.

BACKGROUND OF THE INVENTION

Acoustic techniques for formation characterization are well known. All of these techniques involve transmitting an acoustic signal from a source to a receiver via the formation of interest. The frequency of the signal can vary from very low frequencies in seismic applications through sonic frequencies to ultrasonic frequencies, depending on the particular technique used. Most borehole logging involves the measurement of the time for a sonic signal to pass substantially directly from the source to the receiver via the formation at the borehole wall. Often the measurement is designed to record these direct arrivals and to exclude any signals due to reflections. Alternatively the received signals might be filtered to remove any signal due to reflections.

Seismic surveys generally involve the use of reflected acoustic signals, typically at very low frequencies, to detect structures below the earth's surface. The source of the signals and/or the detectors are usually located at the surface. Borehole seismic techniques place one of these inside the borehole.

In borehole acoustic reflection surveys, the measurements are made with acoustic transmitters and receivers placed in the same borehole. This configuration is best suited for recording reflected wave fields from acoustic reflectors that have small angles with the boreholes axis. For example, near-vertical fractures, faults and salt-dome flanks are

good borehole reflection targets for near-vertical wells. Near-horizontal bed boundaries, fluid contact interfaces (gas/oil or oil/water) and stringers inside reservoirs are good targets for highly-deviated and horizontal wells. The desired events (reflections) in borehole reflection surveys are the waves that propagate from the borehole to the reflector in the formation and back to the borehole. A significant portion of the acoustic energy from the transmitter, however, propagates directly to the receiver array. These direct waves include compressional- and shear-headwaves, tube waves (Stoneley waves), fluid and borehole modes and various casing modes if the well is cased. The direct waves may also include various tool modes that propagate along the tool body. In acoustic logging applications some of these direct waves, e.g. the headwaves and Stoneley waves, are used to log formation properties. In reflection survey applications, however, they are unwanted. The direct waves are typically much larger than reflections.

Reflection imaging around a well using downhole acoustic measurements has been proposed previously, in particular for use in horizontal wells for determining the position of the top or bottom of a reservoir in relation to the borehole. US Patent No. 4,833,658 discloses a method of processing signals to determine the positions of reflectors around a horizontal well. Figure 1 shows the system described in the '658 patent. A tool 5 comprises four transmitters E_1 - E_4 and twelve receivers R_1 - R_{12} positioned in a horizontal borehole 1 at the end of a drill string 30 coupled to a drilling derrick 31 at the surface. The transmitters are separated from each other by a constant interval equal, for example, to 0.25m, and the receivers are separated from each other by a constant interval equal, for example, to 1m. The separation of the closest transmitter and receiver is sugested as 1m. The length of the tool is selected to be at most equal to the distance between the borehole and the most distant reflecting structure (interface 13, 15) of interest. The tool 5 is logged along the borehole 1 and the transmitters E operate to produce acoustic signals with frequencies in the range of 5,000 - 10,000 Hz and the receivers R receive both direct and reflected waves. The received signals are analysed to determine the average propagation velocities of the direct (refracted) and reflected waves. A time section is determined from the signals corresponding to the reflected waves and the time section is converted to a depth section by means of the average propagation

velocity of the reflected waves. The position of the reflecting interface is determined from this depth section. While the approach and parameters suggested in the '658 patent will work in some cases, there are many cases in which they will not. The '658 patent does not recognize this and provides no teaching which would suggest appropriate modifications to the technique to allow it to work in all circumstances.

It is an object of the present invention to provide a technique for reflection acoustic logging in which the problems identified above are less significant and which will allow measurements to be made in a wider range of formations.

SUMMARY OF THE INVENTION

A method of imaging formations surrounding a borehole according to the invention comprises determining the diameter of the borehole; determining an acoustic attenuation property of the formations; determining a range of interest for depth of investigation into the formation from the borehole; positioning a tool in the borehole, the tool having at least one monopole transmitter and at least one acoustic receiver separated therefrom by a distance selected according to the range of interest of the depth of investigation; transmitting, with the at least one monopole transmitter, acoustic signals into the formation at a frequency selected according to the diameter of the borehole, the acoustic attenuation property of the formation and the range of interest for depth of investigation; receiving the acoustic signals at the at least one receiver which have been reflected from structures within the formation; analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

Apparatus according to the invention for imaging formations surrounding a borehole, comprises a tool body; at least one monopole transmitter positioned on the tool body for transmitting acoustic signals into the formation at a frequency selected according to

borehole diameter, a predetermined acoustic attenuation property of the formation and the range of interest for depth of investigation; at least one acoustic receiver positioned on the tool body and separated from the at least one transmitter by a distance selected according to a range of interest of depth of investigation, the at least one receiver receiving the acoustic signals which have been reflected from structures within the formation; means for analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and means for generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

By taking into account the attenuative properties of the formation, the effect of borehole diameter and the desired depth of investigation, it is possible to configure and operate the tool so as to optimize performance over a range of conditions which has not been previously possible.

One particularly preferred use of the invention is the imaging of the formation around the borehole, especially when the borehole is horizontal. The reflected signals can be analyzed to identify the position of reflecting structures such as reservoir boundaries, salt domes or fractures in the formation relative to the borehole and the positions can be represented as an image which can be used to characterize the formation.

It is preferred to use one or more transmitters and an array of receivers. While a single transmitter can be used in certain circumstances, the range of depths of investigation is often limited. Thus the use of more than one transmitter is preferred so as to provide sufficient range in the transmitter to receiver spacing to provide a good range of depths of investigation. Two or three transmitters are believed to provide the best compromise between range and the physical and operational requirements of a borehole tool. Axial receiver arrays provide increased reflected event amplitudes with respect to the tube waves. A typical receiver array will comprise eight axial receiver stations with each station separated by an equal distance, for example six inches. Azimuthal receiver arrays allow the determination of the azimuthal position of reflecting bodies in the formation with respect to the borehole. Four hydrophones disposed around the tool axis at each

receiver station are preferred. By recording the waveforms at each hydrophone at each station, signals can be compared and the direction from which the reflection has arrived can be determined.

The frequency of the transmitted acoustic signals is selected according to borehole diameter, the nature of the formation and the desired range of investigation. Frequencies can range from 100Hz or lower for long range imaging in an attenuative medium to 20kHz or higher for short range, high resolution imaging in a non-attenuative medium. For typical monopole sources suitable for the present invention, the frequency is usually in the range of 1 kHz to 15 kHz.

In order to prevent part of the direct tube wave signal from propagating past the receiver (or transmitter) and reflecting back to the receiver from structures inside the borehole so as to interfere with the reflected signals from the formation, it is preferred to used one or more attenuators positioned in the tool string. These are preferably of the form described in co-pending application no. 08/527,736 (incorporated herein by reference).

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a general schematic view of a prior art borehole reflection imaging system;

Figure 2 shows a schematic view of a borehole reflection imaging system according to the invention;

Figure 3 shows a monopole source for use in the invention; and

Figure 4 shows a plot of the headwave arrivals limiting the detection of reflected signals.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 2 shows a schematic view of a borehole acoustic reflection imaging system according to one embodiment of the present invention. A sonic reflection imaging tool 10 is shown lowered on an armored multiconductor cable 12 into a borehole 14, which can be cased or uncased, to make sonic measurements for imaging of the subsurface

formation 16. In cases where the borehole is deviated from vertical, especially when horizontal, the cable 12 can be run inside drill pipe or tubing such as coil tubing which allows the tool 10 to be pushed into the well when gravity is insufficient or unable to move the tool to the depth of interest. The tool 10 is provided with transmitters 18a, 18b, 18c and a receiver array 20 immediately adjacent thereto which are described in more detail in US Patents Nos. 4,850,450, 5,036,945 and 5,043,952 all of which are incoporated herein by reference. The separation of the transmitter and receiver array is achieved by using a spacing body 19 which incoporates a sonic isolation joint such as is described in US Patent No. 5,036,945. The length of the spacing body 19 is selected according to the range of interest of the depth of investigation. For example, a typical length of a spacing body is 32' and the overall distance from the farthest transmitter 18a to the farthest extent of the receiver array 20 is 43'. One or more tube wave attenuators 22 can be provided at both ends of the transmitter/receiver array section to reduce interfering effects of reflected tube waves in the borehole. These attenuators and their function are described in detail in co-pending application no. 08/527,736, incorporated herein by reference. Such attenuators can also be used between transmitters and the receiver array if required. An orientation device (e.g GPIT tool of Schlumberger including magnetometers and accelerometers) 23 and a telemetry cartridge 24 complete the downhole tool.

The tool 10 is adapted from movement up and down borehole 14, and as the tool 10 is moved, the transmitters 18 periodically generate sonic signals. The generated sonic signals travel through the borehole and/or through the formation where they are reflected by underground structures, and the receivers in the receiver array 20 typically detect some energy which results from the generated signals. The mechanism for moving the tool 10 in the borehole includes the cable 12 which extends to the sheave wheel 25 at the surface of the formation, and then to a suitable drum and winch mechanism 26 which raises and lowers the tool 10 in the borehole as desired. Electrical connection between transmitter array 18 and receiver array 20 on the one hand, and the surface equipment on the other hand, is made through suitable a multi-element slipring and brush contact assembly 28 associated with the drum and winch mechanism 26. A unit 30 contains tool control and pre-processing circuits which send electrical signals to the tool 10 and receive other electrical signals (sonic logs) therefrom via cable 12 and assembly 28. The unit 30 cooperates with a depth recorder 32 which derives depth level signals from a depth measuring wheel 34 so as to associate the signals from receiver array 20 with respective

depth levels in borehole 14. The outputs of the receiver array 20, after optional pre-processing in unit 30, are sent to signal storage 36, which can also receive signals from or through depth recorder 32 so as to associate sonic receiver outputs with respective depth levels in the borehole 14. Storage 36 can store the outputs of the receiver array 20 in the form of digital sonic log measurements. Storage 36 can comprise a magnetic storage device such as a disk or tape, and/or other storage media such as semiconductor or equivalent memory circuits. The stored digital data can then be processed to provide an image of the underground formation surrounding the borehole either as a printed image or displayed on a VDU 38. Kirchhoff-type migration of the data, such as is commonly used in seismic processing, is used to derive the image of the reflecting structures around the borehole.

Each transmitter 18a, 18b, 18c comprises a monopole source which is substantially as described in US Patent No. 5,043,952 (incorporated herein by reference) and shown in Figure 3. These are substantially the same as the monopole source used in conventional sonic logging applications. The source comprises piezo-ceramic cylinder 40 held in an oil filled cavity 42 defined by a corrugated container 44, the corrugations of which allow for differential changes in volume between the mud outside and the oil inside the corrugated container. A power amplifier is attached to the piezo-ceramic cylinder 40 via an electrode 46 for polling the cylinder radially. The electrode 46 is attached to the inner and outer surfaces of the piezo-ceramic cylinder 40 for applying a voltage to the cylinder which causes it to expand in length and radius, thereby causing a volumetric expansion resulting in the generation and propagation of compressional waves into the borehole, and of both compressional waves and shear waves into the formation.

In order to radiate acoustic energy efficiently, the transmitters 18 are designed to operate near geometrical resonances which unavoidably will ring for a long time. A damping mechanism has been introduced to stop this ringing which comprises a rubber-tungsten backing material 48 for the acoustic signal source to provide a good impedance match as well as damping to the attached structure. The rubber-tungsten backing also prevents the additional fluid mode excitation when the transducer is immersed in the fluid. The

rubber- tungsten composite comprises a butyl rubber skeleton loaded with tungsten powder. The impedance and attenuation of the backing will depend on the percentage of tungsten, the degree of compaction of the powder and the degree of vulcanization as well as adherence of the rubber onto the powder.

In Figure 2 three transmitters are shown although it will be appreciated that the invention can be performed with more or less transmitters than this. For example, two transmitters can give a range for the depth of investigation of the order of 30' which would be adequate in certain circumstances. The spacings between the transmitters has been selected to achieve a wide range of depths of investigation. The separation between transmitter 18a and 18b is about 4' and between transmitter 18b and 18c is about 3'6". The considerations for selecting the best spacing for given circumstances are discussed in more detail below. A hydrophone is positioned in transmitter 18c for the purpose of monitoring the output of the source. This hydrophone optionally can also be used as a short spaced receiver. The spacing between transmitter 18c and the receivers can be increased to provide an increased depth of investigation. Alternativley, the spacings between the transmitters can be increased to provide multiple depths of investigation.

The receiver array 20 comprises eight receiver stations spaced 6" apart vertically, each station having four hydrophones disposed circumferentially at 90^0 intervals about the tool making a total of 32 hydrophones. This array is described in detail in US Patent No. 5,036,945. The signals detected at each hydrophone are recorded separately and the signals received by the array analyzed to provide the direction and distance of reflecting structures from the borehole.

The orientation device 23 allows the position and orientation of the tool in the borehole to be determined. Accordingly, the direction from which the reflections arrive can be determined and it is possible to determine whether a reflector is above or below the borehole in a horizontal well, or its direction relative to the borehole in a vertical well.

The imaging range (window) of reflectors away from the borehole is limited due to several reasons. First, in most cases this window, shown as region X in Figure 4, is terminated by the shear-headwave and tube waves which are typically much larger than the reflected compressional waves. For a reflector parallel to the borehole axis, the arrival time of a compressional-wave reflection is approximately given by

$$time_{ref} \approx \frac{1}{v_p}\sqrt{4range^2 + offset^2} \qquad (1)$$

where *range* is the distance of the reflector from the borehole, *offset* is the transmitter-receiver offset, and v_p is the compressional-wave speed. The direct shear wave arrival times, defining the end of the imaging window, are given by

$$time_{dir} \approx offset / v_s \qquad (2)$$

The maximum distance from the borehole, that can be imaged with the large-offset approach, is obtained by setting equation (1) equal to (2) and solving for range, giving

$$range_{\max} \approx 0.5 offset \sqrt{\left(\frac{v_p}{v_s}\right)^2 - 1} \qquad (3)$$

For example, for a typical value of $\frac{v_p}{v_s} = 1.73$, the maximum range is given by $range_{\max} \approx 0.7 offset$. In more general form, v_s above represents the velocity of the first dominating direct wave following the compressional headwave. There is also a minimum range limit. Reflections from very-close reflectors can be masked by the ringing of the direct waves. The duration of the ringing is inversely proportional to the bandwidth of the direct wave, and it very much depends on the acquisition parameters such as the spectral output of the transmitter. Resonance frequencies of the interfering direct waves should be avoided to reduce the ringing duration. For example, for a formation with compressional

velocity of 10,000 ft/sec (100 μsec/ft), the minimum range is approximately 5 ft for 1 kHz bandwidth, and 10 ft for 500 Hz bandwidth.

The second reason for the range limitation is the rapid decrease in reflected-wave amplitudes due to geometrical spreading and attenuation. Amplitude decrease due to geometrical spreading is approximately proportional with the total distance traveled by, or the arrival time of, the reflected event. The amplitude decrease at large offsets due to attenuation can be even more significant than the geometrical spreading. The dependence of the reflected-wave amplitudes on attenuation, frequency and distance is given by

$$amplitude_{ref} \propto \exp\left\{-\frac{\pi f}{v_p Q} d\right\} \tag{4}$$

where f is the frequency, d is the reflection ray path, and Q is a number representing attenuation properties of a medium. Q values can vary significantly, from 5 for a very attenuative medium to 100 for an ideally non-attenuative medium. The above equation shows that amplitude decrease due to attenuation increases exponentially with the propagation path length of the reflected event which increases with the offset. The frequencies employed can range from 100 Hz (or lower) for long-range imaging in attenuative medium, to 20 kHz (or higher) for short-range, high-resolution imaging in non-attenuative medium.

The duration of each pulse from the source and the number of measurements made at the receiver array for each pulse depends on the ability of the system to record data. It may be necessary or desirable to use a number of pulses and record the data from different sets of hydrophones for each pulse which are then stacked to ensure that measurements are made for all combinations of transmitter and receiver in the array. This can be done while moving the tool through the borehole a normal logging speeds.

The signals received by each of the hydrophones are treated in essentially the same manner as signals received by hydrophones in a seismic array and an image is produced

using the same techniques. Thus an image can be produced along the borehole axis (depth axis) and azimuthally around the borehole. By recording complete waveforms at each azimuthal hydrophone position, it becomes possible to determine the time at which a given reflected signal is detected at each position and hence the direction from which it has arrived. For example,in a horizontal borehole, if a given reflection is detected first at the uppermost hydrophone followed by detection at lower hydrophones, the reflecting structure can be indentified as being above the borehole, and vice versa for a reflector below the borehole.

The apparatus descibed above for making reflection measurements in a borehole might also be used to obtain conventional refracted data for evaluation of formation properties in a known manner, in which measurements considered unneccessary for this invention such as headwave measurements, might be used to determine formation parameters. Also, the general approach described above can be applied to cross-well imaging provided that the wells are sufficiently close together.

The present invention is applicable to both wireline and logging-while-drilling applications. In LWD applications, the apparatus forms part of a bottom hole assembly above a drill bit, in the manner of previously proposed LWD sonic logging tools.

WE CLAIM

1 A method of imaging formations surrounding a borehole, comprising:

a) determining the diameter of the borehole;

b) determining an acoustic attenuation property of the formations;

c) determining a range of interest for depth of investigation into the formation from the borehole;

d) positioning a tool in the borehole, the tool having at least one monopole transmitter and at least one acoustic receiver separated therefrom by a distance selected according to the range of interest of the depth of investigation;

e) transmitting, with the at least one monopole transmitter, acoustic signals into the formation at a frequency selected according to the diameter of the borehole, the acoustic attenuation property of the formation and the range of interest for depth of investigation;

f) receiving the acoustic signals at the at least one receiver which have been reflected from structures within the formation;

g) analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and

h) generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

2 A method as claimed in claim 1, wherein the frequency is selected so as to avoid the resonant frequency of headwaves travelling from the transmitter to the receiver.

3 A method as claimed in claim 1, wherein the frequency is selected to optimize coupling of reflected acoustic signals into the borehole.

4 A method as claimed in claim 1, wherein acoustic signals of more than one frequency are transmitted and detected.

5 A method as claimed in claim 1, comprising transmitting acoustic signals from a plurality of transmitters, which are spaced from the at least one receiver by differing distances so as to increase the range of depth of investigation

6 A method as claimed in claim 1, comprising receiving reflected acoustic signals with an array of receivers.

7 A method as claimed in claim 1, comprising receiving reflected signals at a purality of azimuthal positions around the tool.

8 A method as claimed in claim 7, further comprising analyzing the received signals to determine the direction of the reflecting structures from the borehole.

9 A method as claimed in claim 7, wherein complete waveforms are recorded at each azimuthal position.

10 Apparatus for imaging formations surrounding a borehole, comprising:

a) a tool body;

b) at least one monopole transmitter positioned on the tool body for transmitting acoustic signals into the formation at a frequency selected according to borehole diameter, a predetermined acoustic attenuation property of the formation and the range of interest for depth of investigation;

c) at least one acoustic receiver positioned on the tool body and separated from the at least one transmitter by a distance selected according to a range of interest of depth of investigation, the at least one receiver receiving the acoustic signals which have been reflected from structures within the formation;

d) means for analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and

e) means for generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances.

11 Apparatus as claimed in claim 10, wherein the acoustic receiver comprises an axial array of hydrophones.

12 Apparatus as claimed in claim 10, wherein the acoustic receiver comprises a radial array of hydrophones

13 Apparatus as claimed in claim 10, wherein at least two axially spaced transmitters are provided on the tool body.

14 Apparatus as claimed in claim 10, wherein the frequency of the acoustic signals is in the range 1 kHz to 15 kHz.

15 Apparatus as claimed in claim 12, wherein the radial array comprises hydrophones disposed at 90° intervals around the tool body.

16 Apparatus as claimed in claim 15, wherein each hydrophone records substantially complete waveforms.

17 Apparatus as claimed in claim 16, wherein the means for analyzing the received acoustic signals analyzes the waveforms from each hydrophone so as to determine the direction of the reflecting structure from the borehole.

18 Apparatus as claimed in claim 10, further comprising an acoustic receiver positioned at the at least one transmitter.

19 Apparatus as claimed in claim 11, wherein the axial array comprises eight substantially equidistantly spaced receiver stations.

20 Apparatus as claimed in claim 19, wherein each receiver station comprises four hydrophones disposed at 90° intervals around the tool body.

ABSTRACT

A method of imaging formations surrounding a borehole, includes the steps of determining the diameter of the borehole; determining an acoustic attenuation property of the formations; determining a range of interest for depth of investigation into the formation from the borehole; positioning a tool in the borehole,transmitting acoustic signals from the tool into the formation; receiving the acoustic signals at the tool which have been reflected from structures within the formation; analyzing the received acoustic signals to determine the distances of the reflecting structures from the borehole; and generating an image of the position of the reflecting structures with respect to the borehole on the basis of the determined distances. The tool has at least one monopole transmitter and at least one acoustic receiver separated from the transmitter by a distance selected according to the range of interest of the depth of investigation. The frequency of the acoustic signal is selected according to the diameter of the borehole, the acoustic attenuation property of the formation and the range of interest for depth of investigation.